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Spectroscopy with trapped highly charged ions

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Abstract
We give an overview of atomic spectroscopy performed on electron beam ion traps at various locations throughout the world. Spectroscopy at these facilities contributes to various areas of science and engineering, including but not limited to basic atomic physics, astrophysics, extreme ultraviolet lithography, and the development of density and temperature diagnostics of fusion plasmas. These contributions are accomplished by generating, for example, spectral surveys, making precise radiative lifetime measurements, accounting for radiative power emitted in a given wavelength band, illucidating isotopic effects, and testing collisional–radiative models. While spectroscopy with electron beam ion traps had originally focused on the x-ray emission from highly charged ions interacting with the electron beam, the operating modes of such devices have expanded to study radiation in almost all wavelength bands from the visible to the hard x-ray region; and at several facilities the ions can be studied even in the absence of an electron beam. Photon emission after charge exchange or laser excitation has been observed; and the work is no longer restricted to highly charged ions. Much of the experimental capabilities are unique to electron beam ion traps, and the work performed with these devices cannot be undertaken elsewhere. However, in other areas the work on electron beam ion traps rivals the spectroscopy performed with conventional ion traps or heavy-ion storage rings. The examples we present highlight many of the capabilities of the existing electron beam ion traps and their contributions to physics.

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(Some figures in this article are in colour only in the electronic version.)

1. Introduction

More than 20 years ago, the first electron beam ion trap, now dubbed EBIT-I, was put into service to study the physics of highly charged ions interacting with a monoenergetic electron beam [1]. The new device, operated at the Lawrence Livermore National Laboratory, was specifically designed for spectroscopy. It provided direct line of sight access to the ions in the trap by using a set of Helmholtz coils to generate the magnetic field without blocking the view of the trapping region. This was an important departure from using a solenoid, which was the method of choice for electron beam ion sources at the time [2]. The device was immediately successful as a spectroscopic light source. Though it was much dimmer than other light sources, such as tokamaks or laser-plasma sources, it made up for it by allowing continuous operation and unsurpassed control over the operating conditions.

Initial experiments with the EBIT-I electron beam ion trap centered on studying the x-ray emission of various ions, notably for x-ray laser research [3]. However, it became quickly apparent that the device could be used for measurements in a variety of wavelength bands [1, 4]. Various novel operating regimes were developed that extended its usefulness to measuring not only transition energies, but also radiative decay rates, electron-impact excitation and ionization cross sections, dielectronic recombination rates and ionization equilibria under quasi-Maxwellian temperature

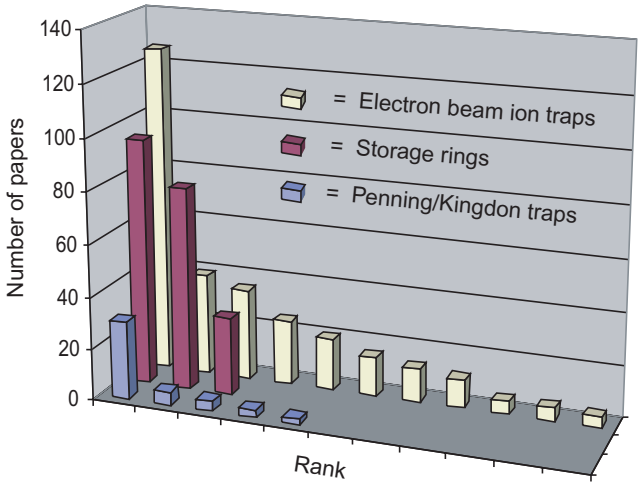

Figure 1. Number of papers published in physics and astronomy journals between 2000 and 2006 by different facilities utilizing trapped highly charged ions. The facilities leading the publication list in each category are the SMILETRAP Penning facility [135] at Stockholm University in Sweden, the Experimental Storage Ring heavy-ion storage ring facility at GSI Darmstadt in Germany [136], and the electron beam ion trap facility at Livermore in California [1].

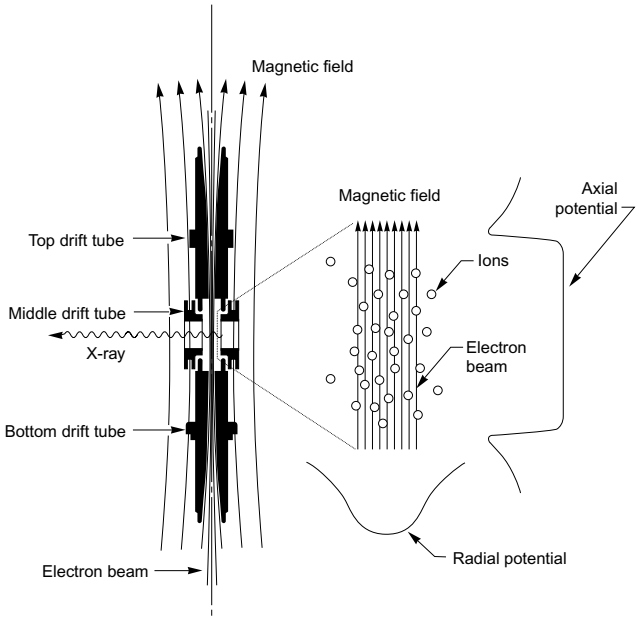

Figure 2. Schematic of the heart of an electron beam ion trap. The electron beam passing through the trap is compressed by a strong axial magnetic field. Ions are confined radially by the space charge of the electron beam and by axial magnetic field. They are confined axially by the electric potential applied to the top and bottom electrodes, i.e. to the top and bottom drift tubes. Axial slots in the middle drift tube allow an unimpeded view of the trapped ions.

conditions [1]. The development of the magnetic trapping mode [5–7], for example, in which the electron beam is turned off, allowed the measurement of spectra produced by charge exchange [8]. In this mode, the electron beam ion trap device operates like a Penning trap, and essentially all classes of experiments performed with such traps are now possible with electron beam ion traps. In parallel, dedicated systems for the interrogation of the ions and the detection of the emitted photons, including lasers, microcalorimeters and polarimeters, have been developed for use on electron beam ion traps. These extend the capabilities of traditional spectroscopy and allow new experiments with trapped ions.

On one hand, the electron beam ion trap competes in its capabilities and type of research performed with other types of devices for studying trapped ions, notably heavy-ion storage rings [9]. The electron beam ion traps are, however, considerably cheaper to build and operate, and in many ways they are more versatile. Even when studying ions with charge as high as U^{92+} or Cf^{96+} in an electron beam ion trap, for example, Doppler shifts are not an issue [10]. On the other hand, electron beam ion traps provide data impossible to produce with heavy-ion storage ring facilities and conventional Penning and Kingdon ion traps, and thus provide complementary data. A search of the publication database of the Digital Library for Physics and Astronomy operated by the Smithsonian Astrophysical Observatory (http://adsabs.harvard.edu/physics_service.html) covering the years between 2000 and 2006 reveals that storage ring and electron beam ion trap facilities produced about equal amounts of papers in physics and astronomy using trapped highly charged ions, as shown in figure 1. Of course, not all of these papers concern spectroscopy.

Given the demonstrated utility of electron beam ion traps, it is not surprising that by now about a dozen such devices have been put into operation throughout the world, and new electron beam ion trap devices are still being planned. For example, electron beam ion traps are under construction or have recently been put online at the Harvard-Smithsonian Center for Astrophysics, at the isotope science facility at the Michigan State University, at the Queen's University in Belfast, and at the AlbaNova Physics Center of the University of Stockholm.

In the following, we will give an overview of the physics studied with these devices at various institutions. We point out that atomic spectroscopy of trapped ions is only one of several reasons for operating electron beam ion traps. In fact, several such facilities were built with other purposes in mind, such as to provide ions for collision experiments with extracted ions [11] or as charge breeders for mass measurements of radioactive nuclei [12]. Our focus in the examples we present will be specifically on the spectroscopic research of trapped ions.

2. The electron beam ion trap

The physics behind electron beam ion traps has been described in several publications [2, 13]. The principle that distinguishes electron beam ion traps from electron beam ion sources or other types of traps is the presence of a highly focused (i.e. high current density) electron beam that ionizes, confines, and traps the ions within a relatively small (few cm long) region, as illustrated in figure 2. The ions are longitudinally confined by applying the appropriate voltages to a set of three drift tubes through which the beam passes. Radial confinement is provided by the electrostatic attraction of the electron beam as well as by the axial magnetic field. All three drift-tube voltages float on top of a common potential supplied by a high-voltage power source, and the

electron beam energy is determined by the sum of the applied potentials minus the effective space charge of the beam. The electron beam density at a given beam energy can be selected by varying the beam current and the magnetic confinement fields.

Since the EBIT-I device was built in 1986, various changes to its original design have been made. For example, permanent magnets, which significantly reduce cost, have been substituted in the Dresden devices for the original 3 T superconducting magnet in EBIT-I [14]; by contrast, the electron beam ion trap at Heidelberg (formerly at the University of Freiburg) uses an 8 T superconducting magnet [15], which allows it to accommodate higher electron beam currents. In addition, both higher and lower energy devices have been built. In fact, the various electron beam ion traps that have come online during the past decade differ substantially from each other. To illustrate this point, we show in figure 3 schematics of three recently developed electron beam ion trap devices. The differences in the design are quite dramatic. As a consequence, there are significant differences in performance. These extend from the more obvious performance characteristics, such as the maximum charge state achievable, to more subtle performance characteristics, such as how smeared out a given charge balance may be, the level of neutral background gases, the presence of contaminants or the degree of control over the electron-beam energy and the length of time to achieve ionization equilibrium. Differences also arise from how the trap is filled—with neutral gases, laser ablation [16], wire-probes [17], low-charge ions from arcs or laser sources [18, 19] or ions from radioactive beams [12].

Important for this review is the type of spectroscopic instrumentation in use at the various facilities. While solid-state detectors are ubiquitous, because they provide real-time information on the x-ray production in the device and thus feedback on device performance as operating parameters are tuned, other spectroscopic instrumentation is rather unique to a given facility. The spectroscopic instrumentation at Livermore is probably the most extensive of any facility. It includes a dozen different crystal spectrometers spanning all geometries from flat-crystal spectrometers for broad-band survey and very high-resolution measurements [20–23] to cylindrically bent crystal spectrometers in the von Hámos, Johann and Cauchois geometries [24–27] and spherically bent crystal spectrometers for x-ray line polarization measurements [28]. It also includes multiple grating spectrometers for studying the emission in the EUV, UV and optical wavelength bands [29–33] and various filter and prism-based optical spectrometers [34–36]. High-resolution microcalorimeters at the Livermore electron beam ion trap facility are now in their fourth generation, starting from a single-pixel device [37, 38] that has later been upgraded and used at the electron beam ion trap facility at the National Institute of Standards and Technology (NIST) in Gaithersburg [39], to various 36-pixel arrays developed at the Goddard Space Flight Center [40], which now provide excellent energy resolution even when measuring hard x-rays and gamma rays up to 60 keV [41, 42]. Figure 4 shows the EBIT Calorimeter Spectrometer (ECS) microcalorimeter [43] and the high-resolution EUV grating spectrometer [33]

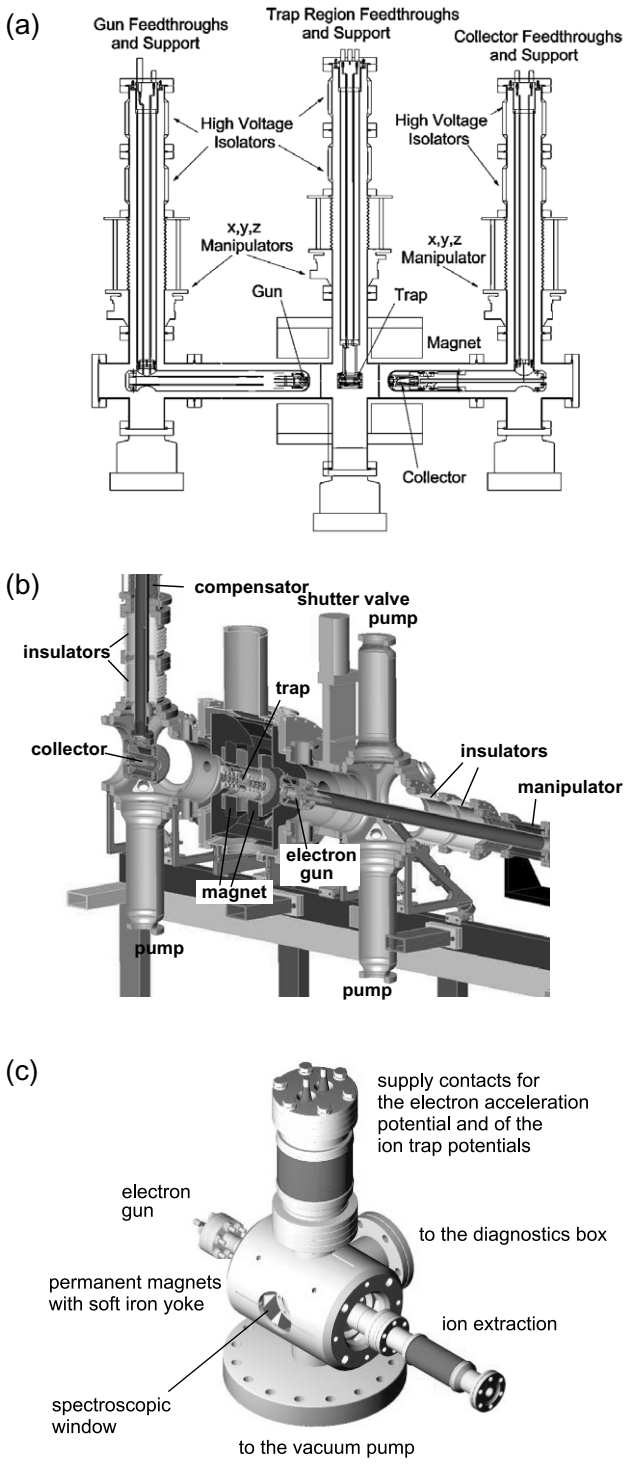

Figure 3. Schematics of electron beam ion traps deployed at (a) the Queen's University in Belfast, Northern Ireland [137], (b) the Tri-University Meson Facility (TRIUMF) in Vancouver, Canada, [12] and (c) the Technical University in Dresden, Germany [138].

on the SuperEBIT high-energy electron beam ion trap at Livermore.

Several electron beam ion trap facilities throughout the world are specifically dedicated to the spectroscopy of highly charged ions. These include the EBIT-I and SuperEBIT devices at Livermore, where essentially all research is conducted *in situ* by viewing the radiation from the ions in the trap [44]. Others are hybrid facilities, which are not only used for *in situ* spectroscopy, but are also used

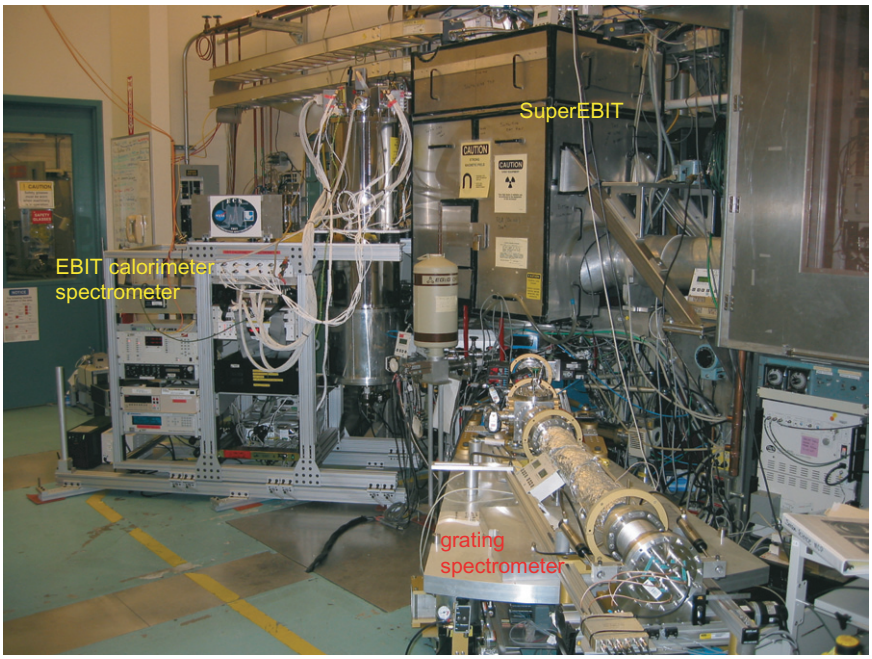

Figure 4. The SuperEBIT facility at the Lawrence Livermore National Laboratory and associated spectroscopic equipment in November 2007.

as ion sources. These include, for example, the facility at Berlin [45] and Tokyo [46]. Here the ions are bred in the trap and then extracted for performing a variety of research, which may include ion–surface interactions or charge-exchange studies. Several electron beam ion trap facilities are essentially exclusively used as ion sources, such as the EBIT-II device [47] after it was moved from Livermore to the Lawrence Berkeley Laboratory, or as charge breeders for nuclear mass measurements developed at TRIUMFs Ion Trap for Atomic and Nuclear science (TITAN) online facility [48].

3. Spectroscopy on electron beam ion traps

In the following, we give brief highlights of work performed *in situ* using spectroscopy. By its nature, this overview will be incomplete, but we hope to touch upon the major aspects of work performed at each institution since the respective machines came into operation.

3.1. New facilities: Stockholm, Shanghai

The electron beam ion trap devices at Fudan University in Shanghai and at the AlbaNova Physics Center of the University of Stockholm are probably the most recent facilities to generate spectroscopic data [49, 50]. Both facilities have performed measurements of the KLL dielectronic resonances using a solid-state detector, as illustrated in figures 5 and 6.

The plot from Stockholm shows the x-rays from near-helium-like silicon ions produced by radiative recombination (RR) and dielectronic recombination (discrete islands) as the electron beam energy was scanned. It also shows the x-rays produced by direct electron-impact excitation (lines at fixed x-ray energy) as the threshold energy for this process is crossed. The plot from Shanghai shows the x-rays from near-helium-like xenon ions produced by dielectronic recombination (discrete islands) as the electron-beam energy was swept over the KLL resonances [51, 52].

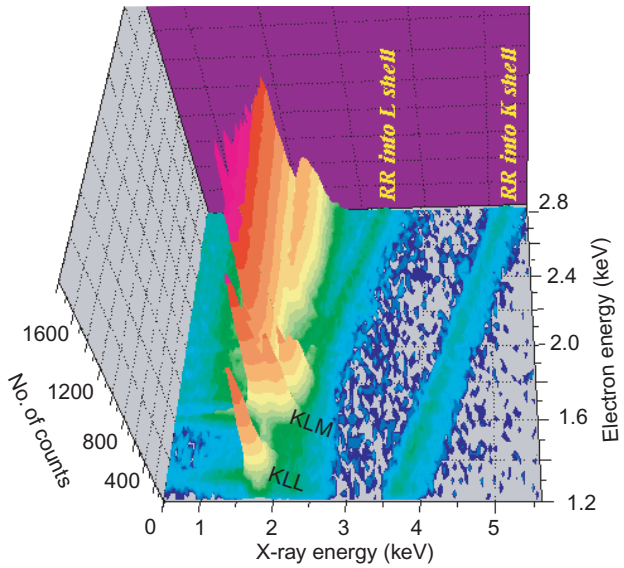

Figure 5. Scatter plot of the x-ray excitation function of near-helium-like silicon ions. The measurement was made at the Stockholm electron beam ion trap facility using a solid-state detector and preparing the ions at a beam energy of 7 keV. (Courtesy of R Schuch.)

3.2. Dresden

The effort at Dresden has focused mainly on the development of cryogen-free, compact electron beam ion traps, and several models have been built so far. These devices utilize warm permanent magnets to compress the electron beam. They are thus unique among the existing devices. Another distinguishing feature has been the intensive use of

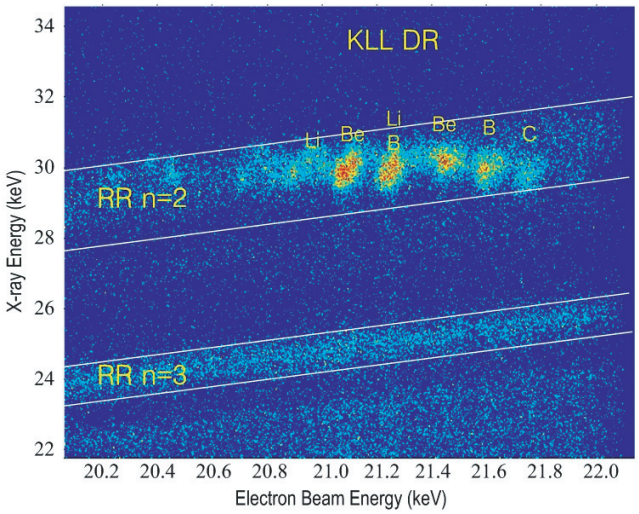

Figure 6. Scatter plot of the x-ray emission from KLL resonance processes involving L-shell xenon ions. The measurement was made at the Shanghai electron beam ion trap facility using a solid-state detector. From [52].

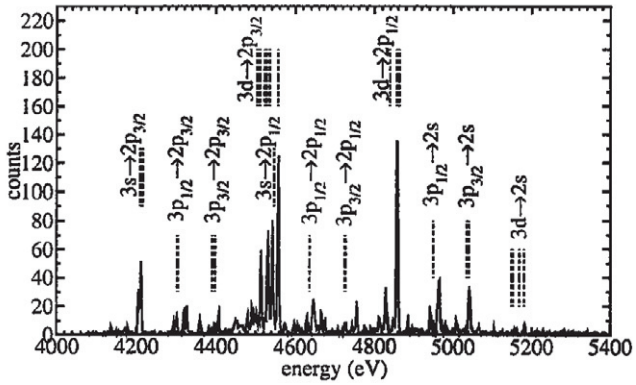

Figure 7. Spectrum of the L-shell emission of neon-like xenon. The measurement was made at the Dresden electron beam ion trap using a flat-crystal spectrometer. From [54].

organo-metallic compounds to fill the trap with metal ions via gas injection [53].

While x-ray scatter plots similar to those shown in figures 5 and 6 have been reported by the Dresden group, they have also used a flat-cystal spectrometer to record the x-ray emisison [54]. The spectrum of neon-like xenon resulting from such a measurement is shown in figure 7.

3.3. Oxford

The electron beam ion trap at the University of Oxford, England, together with the one at NIST were the first to be built outside Livermore [55]. Parts for both were built at Oxford using a slightly modified Livermore design.

The Oxford electron beam ion trap has been used for high-resolution spectroscopy. Significant atomic physics results have been achieved, notably in testing predictions of quantum electrodynamics (QED) and performing accurate transition energy measurements [56–58].

This facility was the first to successfully employ a laser to probe trapped ions. Using a CO_2 laser the Oxford group measured the $2s_{1/2}$–$2p_{3/2}$ energy in N^{6+} to determine the Lamb shift contribution. The transition energy was measured to be $835.0 \pm 0.5\,\mathrm{cm}^{-1}$, in agreement with QED theory [59]. The setup employed in this measurement and the resonance probed with the laser are shown in figure 8.

3.4. Tokyo

The Tokyo electron beam ion trap at the University of Electro-Communications, in Chofu, Japan is the first high-energy electron beam ion trap built outside Livermore [60]. The machine has been equipped to be an ion source. Experiments with extracted ions have yielded important atomic physics results, including cross section studies of dielectronic recombination and x-ray yields from ion–surface interactions [61, 62].

The Tokyo electron beam ion trap has been an important source of spectroscopic data for basic atomic physics. In addition to dielectronic resonance data obtained with solid-state detectors, as illustrated in figure 9, multiple studies involving high-resolution spectroscopy have been performed. For example, a crystal spectrometer provided systematic energy level data on neon-like ions with atomic number Z in the mid-50s [63, 64]. By filling in data along the iso-electronic sequence of earlier measurements on tokamaks [65, 66], the physics of avoided level crossings was illucidated, as shown in figure 10.

Crystal spectroscopy at the Tokyo electron beam ion trap also included a measurement of the K-shell emission of helium-like In^{47+} [67], which is the highest-Z helium-like ion (and the shortest wavelength) observed by a reflection-type crystal spectrometer on an electron beam ion trap. By contrast, the spectrum of helium-like Xe^{52+} was studied on SuperEBIT using a transmission-type crystal spectrometer [68]. Another example of a hard x-ray measurement—possibly not noted by the community—is the determination of the 1s binding energy of hydrogen-like rhodium [69]. This allowed a test of the 1s Lamb shift at the 3.4 eV level.

X-ray line polarization studies on the EBIT-I and EBIT-II devices at Livermore [70–72] and at the electron beam ion trap at Gaithersburg [73] of transitions in helium-like and neon-like ions had found rather good agreement with modern relativistic theory. Reasonable agreement had also been obtained at relativistic electron energies as high as 120 keV [74]. A crystal spectrometer measurement at the Tokyo electron beam ion trap was the first to indicate significant differences with theory. The measurement involved the Lyman-α lines of hydrogen-like Ti^{21+} [75] and had been carried out to energies as high as 50 keV (or 10 threshold units). The results spurred measurements of the Lyman-α lines of Ar^{17+} and Fe^{25+} on SuperEBIT with electron energies as high as 25 threshold units [76]. The results, shown in figure 11, are overall well below theory and appear to confirm that there are unresolved issues for such a simple atomic system.

3.5. Berlin

The electron beam ion trap in Berlin follows the Livermore design for EBIT-II [77]. Most of its focus has been on atomic data for magnetic fusion using a variety of spectroscopic equipment.

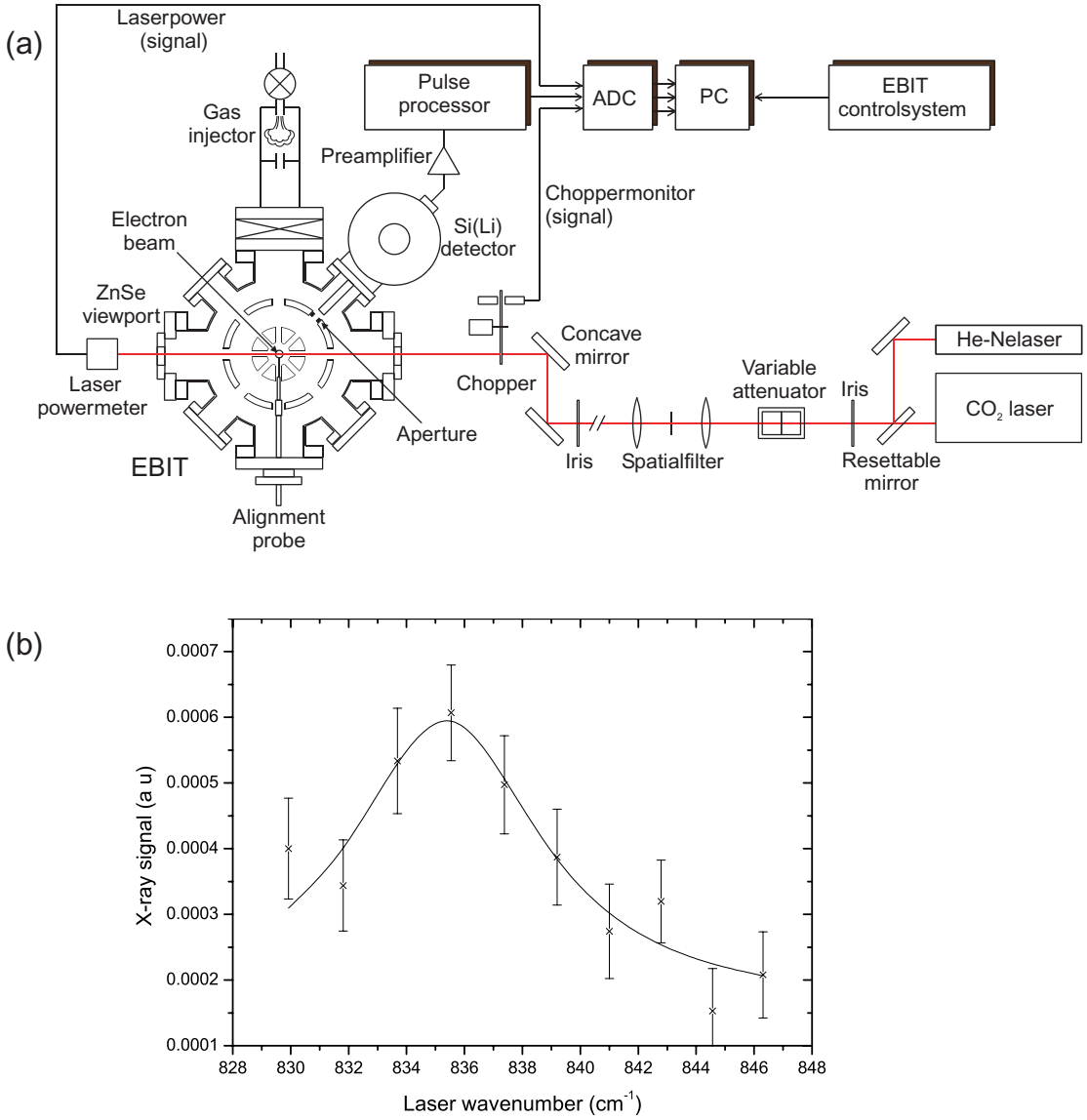

Figure 8. Measurement of the $2s_{1/2}$–$2p_{3/2}$ transition energy in N^{6+} using a laser probe: (a) schematic of the experimental setup on the Oxford electron beam ion trap and (b) observed resonance. Adopted from [59].

A measurement of the excitation function of krypton obtained with a solid-state detector is shown in figure 12(a). Unlike similar measurements at other facilities where the observed emission simply reflects the ionization balance prevalent at the time of the measurement, the ionization balance for the Berlin measurement was specifically chosen to be that predicted for a plasma temperature of 4.7 keV [78]. Under this condition one can use the observed photon emission as a function of beam energy to derive the radiative cooling rate at this temperature by folding the observed emission with the appropriate weight function (shown in figure 12(b)). The resulting cooling rate is shown in figure 12(c), where it is compared to various theoretical predictions.

The Berlin machine is equipped with a versatile EUV spectrograph. Two measurement examples are shown in figures 13 and 14. The spectrum in figure 13 shows the emission of various tungsten ions in the far ultraviolet [79]. This wavelength region has received little attention so far, but is important for impurity monitoring of magnetic fusion plasmas, especially in light of the planned ITER magnetic fusion test reactor [80, 81], which may employ tungsten armor in regions that need to withstand a high heat flux. The spectrum in figure 14 shows the emission of various xenon ions in the extreme ultraviolet [82]. Xenon has been proposed as a coolant to reduce the heat load on the armor plates in future magnetic fusion devices. In both cases the beam energy was stepped through various ionization thresholds in order to aid the line identification.

3.6. Gaithersburg

The electron beam ion trap at NIST in Gaithersburg, is the first such device to operate outside Livermore [83]. The NIST group was the first to report detailed measurements of transitions in highly charged ions in the visible. The particular line studied was the $3d^4\ ^2D_{3/2}$–$3d^4\ ^2D_{5/2}$ transition from titanium-like Xe^{32+} and Ba^{34+} [84]. Unlike other fine structure transitions, this particular transition remains in the visible even as Z increases. For bismuth, its

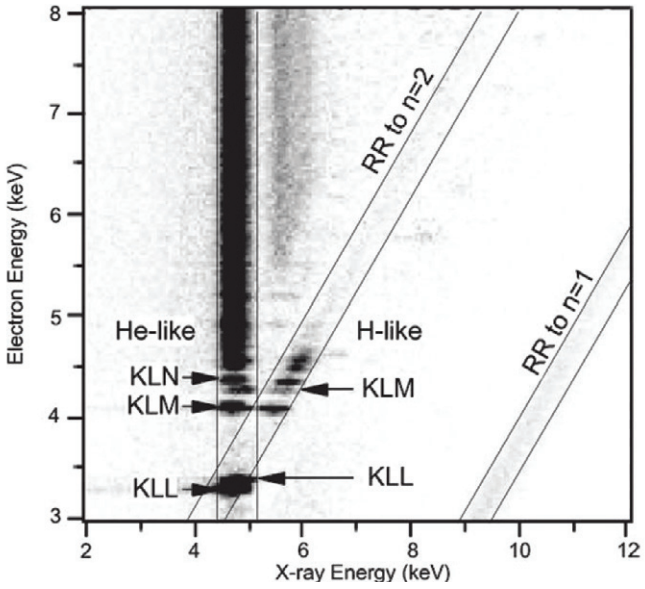

Figure 9. Scatter plot of the x-ray excitation function of helium-like and hydrogen-like titanium ions. The measurement was made at the Tokyo electron beam ion trap facility using a solid-state detector. From [139].

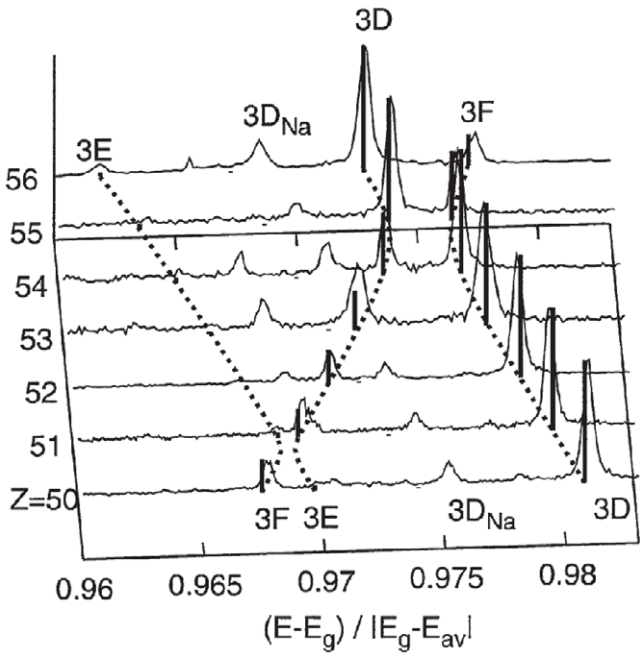

Figure 10. Crystal spectra of the neon-like ions with Z between 50 and 56 observed at the Tokyo electron beam ion trap. The three neon-like transitions affected by avoided level crossings involve the upper states $(2p^5_{3/2}3d_{3/2})_{(J=1)}$, $(2p^5_{1/2}3s_{3/2})_{(J=1)}$ and $(2p^5_{3/2}3d_{5/2})_{(J=1)}$ and are labeled 3E, 3F, and 3D, respectively. From [64].

wavelength is still well above 3400 Å, i.e., it is still in the optical regime. The reported wavelengths were in poor agreement with theory, spurring more experimental and theoretical investigations. Measurements subsequently performed at NIST [85], Tokyo [86], and Livermore's EBIT-II device [87] are shown in figure 15 and compared to improved theory [88].

Line identifications in the optical regime are often complicated by the fact that theoretical predications may

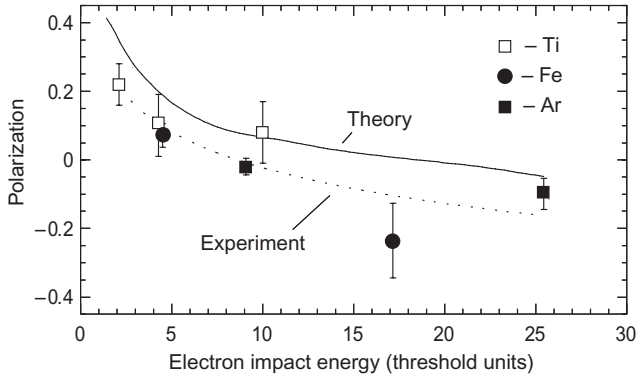

Figure 11. Measured polarization of the Lyman-α_1 line of Ar^{17+} [76], Ti^{21+} [75], and Fe^{25+} [76] compared to the predictions of distorted-wave calculations as a function of electron-impact energy in threshold units. The dotted line represents the best fit of the experimental data.

differ by tens of Ångströms and more. Such differences exist not only in complex, multi-electron ions, such as the just mentioned titanium-like system, but even hydrogen-like systems can differ by such amounts from theory [89, 90]. Identification is greatly helped by the ability to vary the electron beam energy and to see lines appear as the ionization threshold to make the next higher charge state is crossed, as illustrated earlier for lines in the ultraviolet (cf figures 13 and 14). This method was used at Gaithersburg to track from 100 eV to 10 keV the intensity and position of a visible line of xenon of interest in EUV lithography [91]. It was concluded that the line, shown in figure 16, is from Xe^{9+} with a wavelength of 5983.0 ± 1.3 Å. This result was said to correct an earlier measurement at Livermore, which intimated that a line near 5984 Å arose from Xe^{31+} [92]. It was stated that 'We have found no evidence to support the claim by others that a line near this position originates from Xe^{31+}' [91]. This statement was surprising, because the Livermore assignment was also based on varying the beam energy: the line appeared at a beam energy around 1870 eV, i.e., after the threshold for producing Xe^{31+} ions was crossed, and vanished below that energy. This puzzle was partly resolved in a measurement at the Berlin electron beam ion trap (cf figure 17). The group at Berlin found that at low energy there is a line at 5980.4 ± 0.3 Å from Xe^{9+} and that at higher energies there is a line at 5982.1 ± 0.3 Å from Xe^{31+} [93]. Interestingly, the line determined to be from Xe^{9+} has a wavelength (5980.4 ± 0.3 Å) that does not agree with that found by NIST (5983.0 ± 1.3 Å). The wavelength of the NIST line instead agrees instead with the Xe^{31+} line at 5982.1 ± 0.3 Å. Thus, if the NIST wavelength were correct, it would mean that they misidentified their line and actually measured the line observed by Livermore. But because this contradicts their claim that 'Our measurement for the energy dependence of the line intensity rules out that the line we observed originates from Xe^{31+}', it is more likely that the reported wavelength simply is not correct within the uncertainty limits—although the possibility remains that the NIST group measured a line that is neither of those reported by the other electron beam ion trap groups, or vice versa.

The above example illustrates that line identification cannot always rely on merely scanning the electron-beam

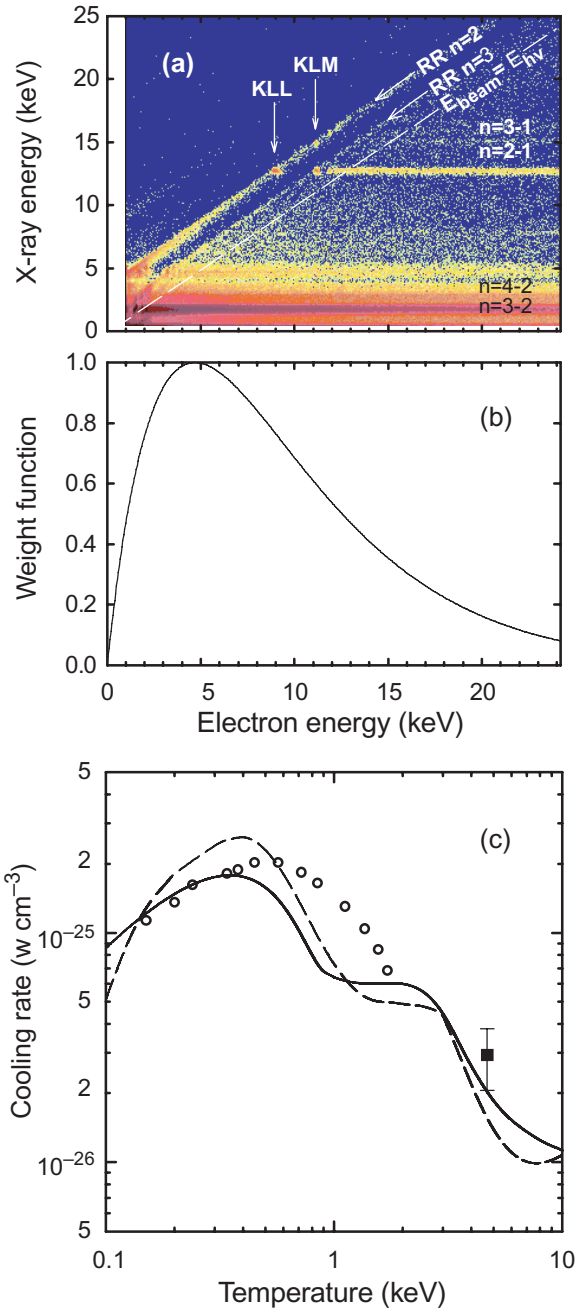

Figure 12. Measurement of the radiative cooling rate of krypton in a 4.7 keV plasma at the Berlin electron beam ion trap: (a) scatter plot of the x-ray excitation function of krypton ions made with a solid-state detector; (b) weight function used to derive the cooling rate from (a); (c) radiative cooling rate of krypton as a function of plasma temperature. Solid and dashed curves are various calculations. The solid square is from the Berlin measurement [78]. The open circles are measurements from the Frascati tokamak [140].

energy. This method works only, if the charge distribution in the machine is narrowly peaked. A broad charge state distribution had been reported earlier from the Gaithersburg electron beam ion trap in the case of Fe^{16+}. From simple charge balance calculations this ion stage is expected to burn out around 1500 eV [94]. This expectation was confirmed in measurements on EBIT-II at Livermore [95]. The Fe XVII x-ray emission was detected, however, at the Gaithersburg electron beam ion trap at beam energies of 4000 eV and beyond [96].

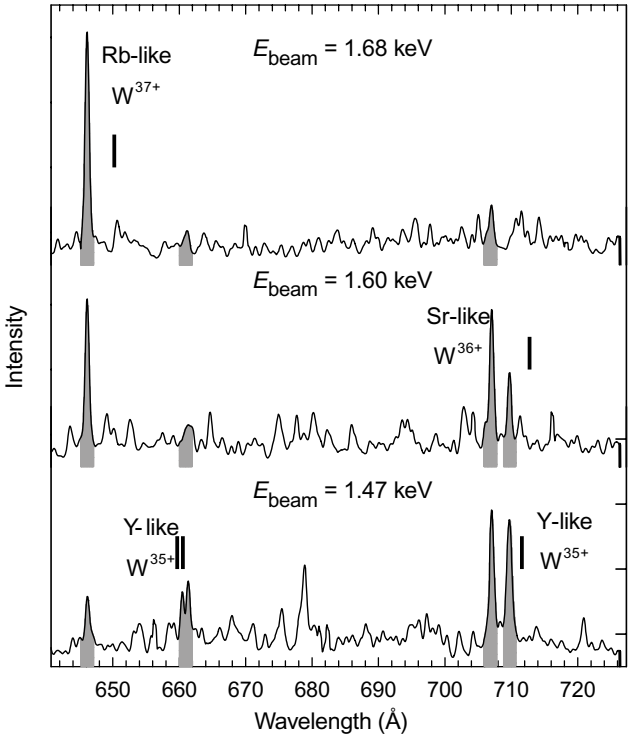

Figure 13. Measurements of FUV spectra of tungsten from the Berlin electron beam ion trap for different electron-beam energies (adopted from [79]). Shaded lines are from tungsten; vertical marks indicate their positions predicted by calculations.

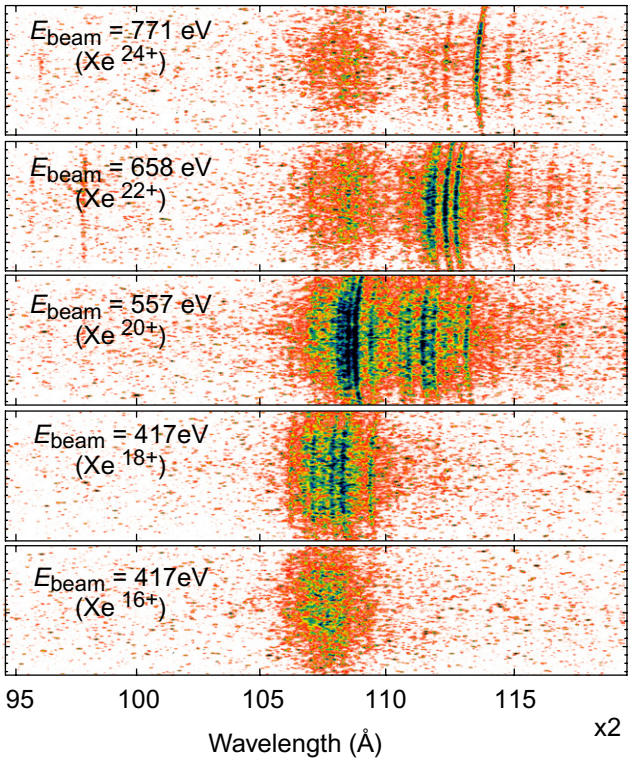

Figure 14. Measurements of EUV spectra of xenon from the Berlin electron beam ion trap for several electron-beam energies (adopted from [82] and figures provided by C Biedermann). The dominant charge state of xenon is indicated.

Effects related to a broad ionization balance may have affected the Gaithersburg measurement of the Fe XVII line intensities [97], which was subsequently determined to be

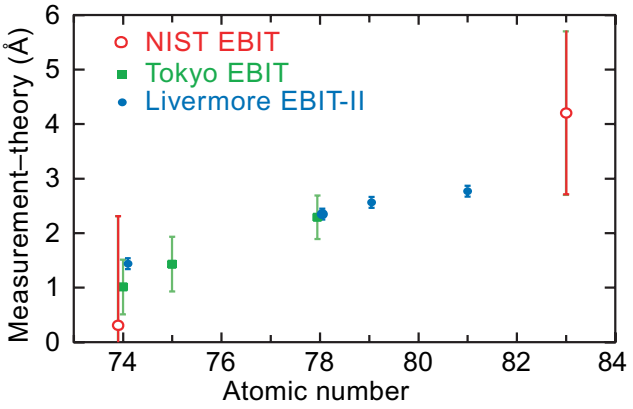

Figure 15. Difference between measured and predicted [88] wavelengths of the $3d^4\ ^2D_{3/2}$–$3d^4\ ^2D_{5/2}$ transition from titanium-like ions. The measurements were performed at NIST (open circles) [85], Tokyo (solid squares) [86], and Livermore's EBIT-II device (solid circles) [87].

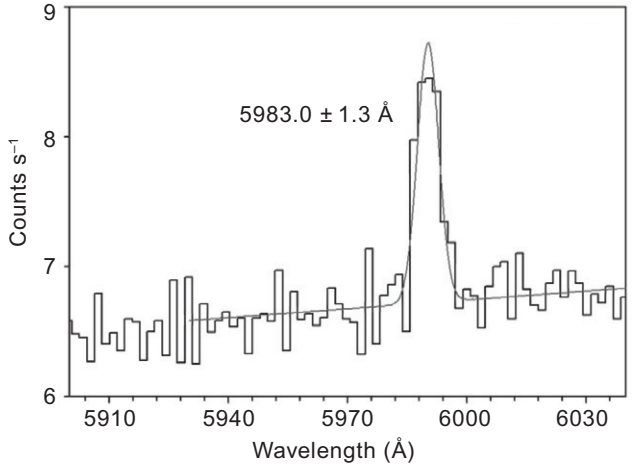

Figure 16. Measurement of the xenon emission at $E_{beam} = 220$ eV from the Gaithersburg electron beam ion trap (adopted from [91]).

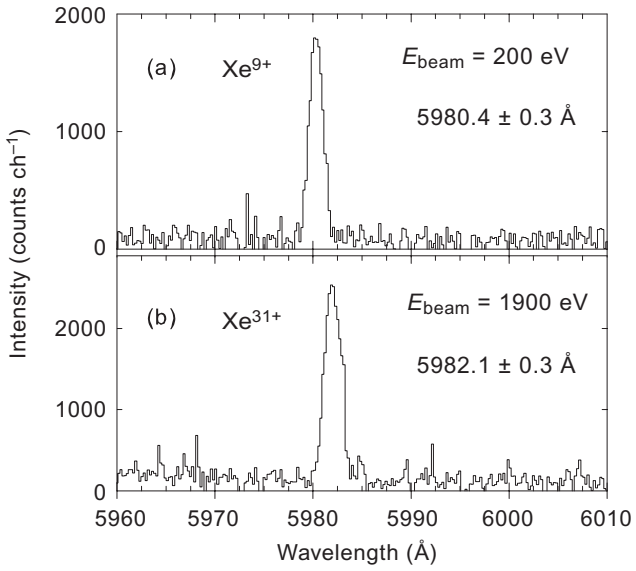

Figure 17. Measurements of the xenon emission at $E_{beam} = 200$ and 1900 eV from the Berlin electron beam ion trap (adopted from [93]).

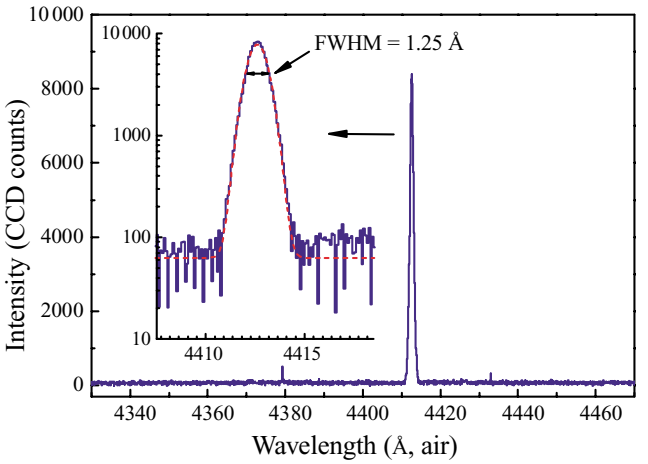

Figure 18. Measurement of the $1s^22s^22p_{1/2}$–$1s^22s^22p_{3/2}$ ground state fine structure transition in boron-like Ar^{13+} from the Heidelberg electron beam ion trap (adopted from [105]).

erroneous [98, 99]. By contrast, a recent measurement at the Gaithersburg electron beam ion trap of Ni XIX [100], which is in the same isoelectronic sequence as Fe XVII, was found to agree well with the earlier Livermore data [101–103].

3.7. Heidelberg

The electron beam ion trap at the Max Planck Institute for Nuclear Physics in Heidelberg was first operated at the University of Freiburg before its move to Heidelberg [15]. Several new machines have been built at Heidelberg since, including the one now operating at TRIUMF and another one used at the free-electron laser at the synchrotron facility in Hamburg [12, 104].

The Heidelberg electron beam ion trap has been used intensively to study the ground state fine structure transition in boron-like Ar^{13+}. The wavelength of this transition was measured with extremely high accuracy, 4412.559 ± 0.001 Å [105], as illustrated in figure 18. The accuracy of the measurement exceeds that of the best calculations by a factor of 3000. These calculations suggest that the line's wavelength is shifted by 9.6 Å due to QED.

In a subsequent measurement even higher precision was achieved by utilizing evaporative cooling [106, 107] to reduce the Doppler motion of the ions in the trap. At ion temperatures as low as 6 eV, the six Zeeman components became readily apparent, as illustrated in figure 19 [108]. Observation of the splitting is aided by the fact that the Heidelberg electron beam ion trap is operated at a field strength of 8 T, which is almost three times higher than that of the Livermore, Berlin, or Gaithersburg machines and 10–20 times higher than that of the Dresden machines. By studying the boron-like fine structure transition both in $^{36}Ar^{13+}$ and $^{40}Ar^{13+}$ an isotope shift of 0.0123 ± 0.0006 Å was determined, which perfectly agreed with predictions [108].

Employing the magnetic mode of operation [6], the Heidelberg electron beam ion trap has also been used to measure the radiative rate of the Ar^{13+} $^2P_{1/2}$–$^2P_{3/2}$ ground state fine structure transition [109]. The Heidelberg measurement of 9.573 ± 0.004 ± 0.005 ms (stat/syst) for the corresponding radiative lifetime achieved a precision that

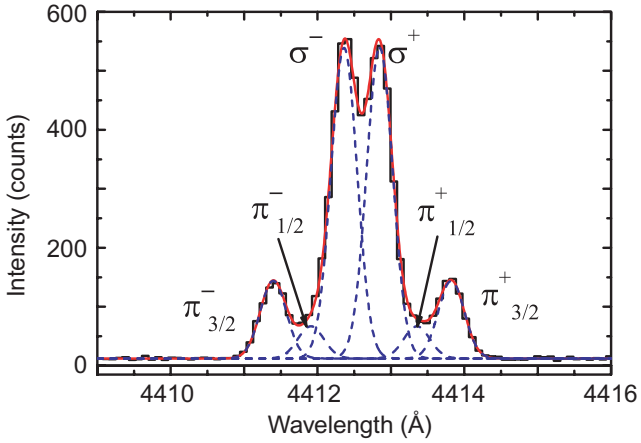

Figure 19. Measurement of the Zeeman components of the $^2P_{1/2}$–$^2P_{3/2}$ ground state fine structure transition in boron-like $^{40}Ar^{13+}$ from the Heidelberg electron beam ion trap (adopted from [108]).

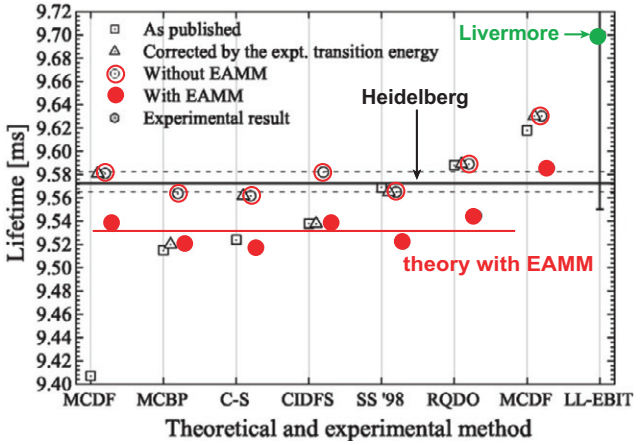

Figure 20. Comparision of the radiative rates of the $1s^22s^22p_{1/2}$–$1s^22s^22p_{3/2}$ ground state fine structure transition in boron-like Ar^{13+} measured at the Heidelberg electron beam ion trap with theory (adopted from [109]). Theoretical values with and without inclusion of the electron anomalous magnetic moment (EAMM) are shown.

exceeded that of previous measurements by more than an order of magnitude. Interestingly, only one of the previous three measurements of this transition agreed within error bars with the Heidelberg result, although all measurements were performed using ions traps. The result in agreement with the Heidelberg measurement is the 9.70 ± 0.15 ms measurement performed at Livermore [110]. The 9.12 ± 0.18 ms result from a measurement using a Kingdon trap is too short [111]; even shorter is the 8.7 ± 0.5 ms result obtained at the Gaithersburg electron beam ion trap [112].

The high accuracy of the Heidelberg radiative lifetime measurement makes it sensitive to the electron anomalous magnetic moment $g-2$. Surprisingly, the calculations thought to be the most accurate and that include the contribution from the electron anomalous magnetic moment differ from the measured value by three σ, while those that do not include the effect are in agreement. This is illustrated in figure 20.

A subsequent measurement performed at the Heidelberg electron beam ion trap centered on the $^2P_{1/2}$–$^2P_{3/2}$ ground

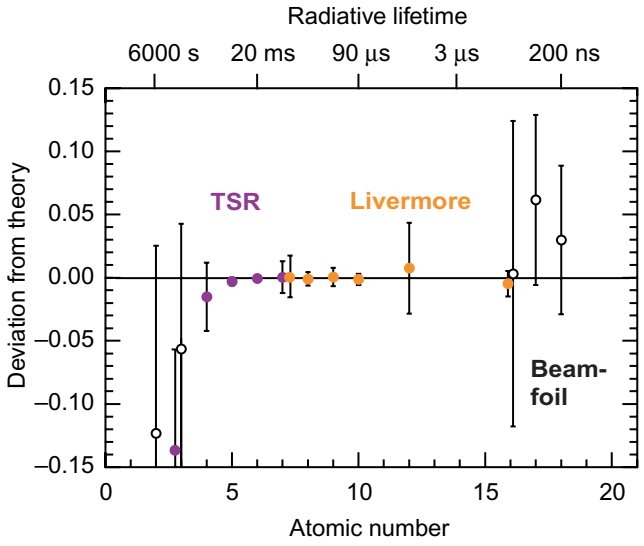

Figure 21. Fractional difference between the radiative lifetimes of the 1s2s $^3S_1$ level in helium-like ions measured at various facilities and theory.

state fine structure transition of aluminum-like Fe^{13+} [113] confirmed the conclusions of the Ar^{13+} measurement. The highly accurate result of $16.726^{+0.020}_{-0.010}$ ms is again in agreement with the earlier Livermore result of 16.74 ± 0.12 ms [114], but it is shorter than the 17.0 ± 0.2 ms and 17.52 ± 0.29 ms results obtained on Kingdon traps [115, 116]. It is also shorter than the 18.0 ± 1.2 ms result obtained at the TSR heavy-ion storage ring at Heidelberg [117]. As noted before for argon, inclusion of the contribution from the electron anomalous magnetic moment destroys agreement with the measured value.

3.8. Livermore

As mentioned earlier, the Livermore electron beam ion traps are the oldest of their kind, and spectroscopic measurements on the SuperEBIT and EBIT-I facility remaining in Livermore have spanned the areas now found at the other electron beam ion trap facilities as well as areas not pursued elsewhere, including measurements in support of magnetic fusion [118], high-energy density physics [119–121], astrophysics [122–124], and basic atomic physics such as highly accurate QED determinations and measurements of electron-impact excitation cross sections [125–127]. In the following we give examples only of recent radiative lifetime measurements. Unlike the measurements already mentioned, the following measurements have been carried out by studying x-ray transitions.

The possibility of radiative lifetime measurements using an electron beam ion trap has been demonstrated first at Livermore in a determination of the 91 μs lifetime of the 1s2s $^3S_1$ excited level of helium-like Ne^{8+} [128]. Since then measurements of helium-like ions at Livermore have explored five orders of magnitude, from tens of milliseconds to hundreds of nanoseconds [129], as illustrated in figure 21. This figure also shows that electron beam ion traps occupy a specific niche for such measurements, in which no other facility currently can perform measurements. This niche is bounded on one end by heavy-ion storage rings and externally

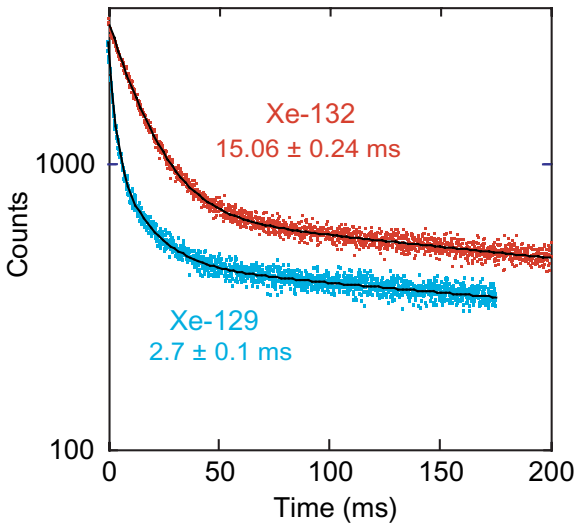

Figure 22. Measurements the radiative decay rates of the $3d^9_{5/2}4s_{1/2}$ $^3D_3$ level in two isotopes of nickel-like Xe^{26+} performed at the SuperEBIT electron beam ion trap (adopted from [134]).

filled ion traps and on the other end by beam-foil and slow recoil ion spectroscopy.

Another example is the measurement of the radiative lifetime of the $3d^9_{5/2}4s_{1/2}$ $^3D_3$ level. This level is the lowest-excited level in the nickel-like isoelectronic sequence. It can decay to the $3d^{10}$ $^1S_0$ ground state only via a magnetic octupole transition, as first observed at Livermore in 1991 [130] and recently rediscovered at the Gaithersburg electron beam ion trap [131]. The radiative rate of the magnetic octupole transition was first measured using the second-generation Goddard microcalorimeter on EBIT-I for Xe^{26+}, Cs^{27+} and Ba^{28+} [132]. The microcalorimeter measurement studied elements with naturally abundant isotope ratios. Odd-nucleon isotopes have a nonzero nuclear magnetic moment, which leads to hyperfine-induced mixing of the $^3D_3$ level with the neighboring $^3D_2$ level. This level decays via an electric quadrupole transition [133] and at a rate orders of magnitude faster than the rate associated with the magnetic quadrupole decay. Measurements on SuperEBIT with isotopically pure Xe^{26+} ions have verified this mixing [134], as illustrated in figure 22, which in $^{129}Xe^{26+}$ shortens the $^3D_3$ lifetime by almost a factor of six.

4. Conclusion

Hopefully this brief overview has successfully illustrated the current vitality of atomic physics studies with electron beam ion traps. Electron beam ion traps occupy a niche that cannot (yet) be touched by other kinds of facilities, including standard ion traps and storage rings. In other areas, electron beam ion traps are highly competitive with these facilities.

Spectroscopy of highly charged ions is not yet a complete field, and new discoveries continue to be made. In addition, there is a great need for spectroscopic data throughout physics, such as astrophysics, high-energy density physics, and fusion research. As a result, electron beam ion traps will continue to be an important platform for generating atomic data and advancing modern physics.

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References

[1] Beiersdorfer P 2008 *Can. J. Phys.* **86** 1
[2] Marrs R E 2008 *Can. J. Phys.* **86** 11
[3] Nilsen J 2008 *Can. J. Phys.* **86** 19
[4] Beiersdorfer P *et al* 2001 *Phys. Scr.* T **92** 268
[5] Beiersdorfer P, Beck B, Marrs R E, Elliott S R and Schweikhard L 1994 *Rapid Commun. Mass Spectrom.* **8** 141
[6] Beiersdorfer P, Schweikhard L, Crespo López-Urrutia J and Widmann K 1996 *Rev. Sci. Instrum.* **67** 3818
[7] Beiersdorfer P, Beck B, Becker S and Schweikhard L 1996 *Int. J. Mass Spectrom. Ion Process.* **158** 149
[8] Beiersdorfer P *et al* 2003 *Science* **300** 1558
[9] Marrs R E 1991 *Comments At. Mol. Phys.* **27** 57
[10] Beiersdorfer P, Elliott S R, Crespo López-Urrutia J and Widmann K 1997 *Nucl. Phys.* A **626** C357
[11] Zschornack G, Großmann F, Heller R, Kentsch U, Kreller M, Landgraf S, Ovsyannikov V P, Schmidt M and Ullmann F 2007 *Nucl. Instrum. Methods Phys. Res.* B **258** 205
[12] Sikler G, Crespo López-Urrutia J R, Dilling J, Epp S, Osborne C J and Ullrich J 2005 *Eur. J. Phys.* **25** 63
[13] Levine M A *et al* 1989 *Nucl. Instrum. Methods* B **43** 431
[14] Zschornack G, Heller R, Kreller M, Landgraf S, Großmann F, Kentsch U, Ovsyannikov V P, Schmidt M and Ullmann F 2006 *Rev. Sci. Instrum.* **77** 03
[15] Crespo López-Urrutia J R, Bapat B, Draganic I, Werdich A and Ullrich J 2001 *Phys. Scr.* T **92** 110
[16] Niles A M, Magee E W, Thorn D B, Brown G V, Chen H and Beiersdorfer P 2006 *Rev. Sci. Instrum.* **77** 10F106
[17] Elliott S R and Marrs R E 1995 *Nucl. Instrum. Methods* B **100** 529
[18] Brown I G, Galvin J E, MacGill R A and Wright R T 1986 *Appl. Phys. Lett.* **49** 1019
[19] Trinczek M, Werdich A, Mironov V, Guo P, González Martánez A J, Braun J, Crespo López-Urrutia J R and Ullrich J 2006 *Nucl. Instrum. Methods Phys. Res.* B **251** 289
[20] Beiersdorfer P and Wargelin B J 1994 *Rev. Sci. Instrum.* **65** 13
[21] Brown G V, Beiersdorfer P and Widmann K 1999 *Rev. Sci. Instrum.* **70** 280
[22] Klöpfel D, Hölzer G, Förster E and Beiersdörfer P 1997 *Rev. Sci. Instrum.* **68** 3669
[23] Beiersdorfer P, Crespo-López Urrutia J R, Förster E, Mahiri J and Widmann K 1997 *Rev. Sci. Instrum.* **68** 1077
[24] Beiersdorfer P, Marrs R E, Henderson J R, Knapp D A, Levine M A, Platt D B, Schneider M B, Vogel D A and Wong K L 1990 *Rev. Sci. Instrum.* **61** 2338
[25] Beiersdorfer P 1997 *AIP Conf. Proc. 389, X-ray and Innershell Processes* ed R L Johnson, H Schmidt-Böcking and B F Sonntag (Woodbury, NY: AIP) p 121
[26] Widmann K, Beiersdorfer P, Brown G V, Crespo López-Urrutia J R, Decaux V and Savin D W 1997 *Rev. Sci. Instrum.* **68** 1087
[27] Beiersdorfer P, Crespo López-Urrutia J, Decaux V, Widmann K and Neill P 1997 *Rev. Sci. Instrum.* **68** 1073
[28] Robbins D L, Chen H, Beiersdorfer P, Faenov A Y, Pikuz T A, May M J, Dunn J and Smith A J 2004 *Rev. Sci. Instrum.* **75** 3717
[29] Beiersdorfer P, Crespo López-Urrutia J R, Springer P, Utter S B and Wong K L 1999 *Rev. Sci. Instrum.* **70** 276
[30] Utter S B, Brown G V, Beiersdorfer P, Clothiaux E J and Podder N K 1999 *Rev. Sci. Instrum.* **70** 284
[31] Utter S B, Beiersdorfer P, Crespo López-Urrutia J R and Träbert E 1999 *Rev. Sci. Instrum.* **70** 288

[32] Utter S B, Crespo López-Urrutia J R, Beiersdorfer P and Träbert E 2002 *Rev. Sci. Instrum.* **73** 3737
[33] Beiersdorfer P, Magee E W, Träbert E, Chen H, Lepson J K, Gu M-F and Schmidt M 2004 *Rev. Sci. Instrum.* **75** 3723
[34] Chen H, Beiersdorfer P, Harris C L, Träbert E, Utter S B and Wong K L 2001 *Phys. Scr.* T **92** 284
[35] Chen H, Beiersdorfer P, Harris C L, Utter S B and Wong K L 2001 *Rev. Sci. Instrum.* **72** 983
[36] Träbert E and Beiersdorfer P 2003 *Rev. Sci. Instrum.* **74** 2127
[37] Le Gros M, Silver E, Beiersdorfer P, López-Urrutia J C, Widmann K and Kahn S M 1996 An electron beam ion trap annual report 1995 *University of California Lawrence Livermore National Laboratory Report* UCRL-ID-124429 (Livermore, CA) p 22
[38] Beiersdorfer P *et al* 2005 *Highlights of Astronomy* vol 13, as presented at the XXVth General Assembly of the IAU—2003 ed O Engvold (San Franciso, CA: Astronomical Society of the Pacific) pp 633–9
[39] Silver E *et al* 2000 *Astrophys. J.* **541** 495
[40] Porter F S *et al* 2008 *Can. J. Phys.* **86** 231
[41] Beck B R, Becker J A, Beiersdorfer P, Brown G V, Moody K J, Wilhelmy J B, Porter F S, Kilbourne C A and Kelley R L 2007 *Phys. Rev. Lett.* **98** 142501
[42] Thorn D B, Brown G V, Clementson J H T, Chen H, Chen M H, Beiersdorfer P, Boyce K R, Kilbourne C A, Porter F S and Kelley R L 2008 *Can. J. Phys.* **86** 241
[43] Porter F S, Beiersdorfer P, Brown G V, Doriese W, Kelley R L, Kilbourne C A, King J, Irwin K, Reintsema C and Ullom J 2008 *J. Low Temp. Phys.* **86** 231
[44] Beiersdorfer P 2005 *Phys. Scr.* T **120** 40
[45] Allen F I, Biedermann C, Radtke R and Fussmann G 2007 *J. Phys. Conf. Ser.* **58** 188
[46] Watanabe H, Tobiyama H, Kavanagh A P, Li Y M, Nakamura N, Sakaue H A, Currell F J and Ohtani S 2007 *Phys. Rev.* A **75** 012702
[47] Schenkel T, Persaud A, Krämer A, McDonald J W, Older J P H, Hamza A V and Schneider D H 2002 *Rev. Sci. Instrum.* **73** 663
[48] Froese M, Champagne C, Crespo López-Urrutia J R, Epp S, Gwinner G, Lapierre A, Pfister J, Sikler G, Ullrich J and Dilling J 2006 *Hyperfine Interact.* **173** 85
[49] Zhu X *et al* 2005 *Nucl. Instrum. Methods Phys. Res.* B **235** 509
[50] Böhm S, Enulescu A, Fritiojj T, Orban I, Tashenov S and Schuch R 2007 *J. Phys. Conf. Ser.* **58** 303
[51] Chen W D *et al* 2007 *Phys. Plasma* **14** 103302
[52] Hu W *et al* 2008 *Can. J. Phys.* **86** 321
[53] Zschornack G, Landgraf S, Grossmann F, Kentsch U, Ovsyannikov V, Schmidt M and Ullmann F 2005 *Nucl. Instrum. Methods Phys. Res.* B **235** 160
[54] Werner T, Zschornack G, Großmann F, Ovsyannikov V and Ullmann F 2001 *Phys. Scr.* T **92** 241
[55] Silver J D *et al* 1994 *Rev. Sci. Instrum.* **65** 1072
[56] Bieber D J, Margolis H S, Oxley P K and Silver J D 1997 *Phys. Scr.* T **73** 64
[57] Tarbutt M R, Barnsley R, Peacock N J and Silver J D 2001 *J. Phys. B: At. Mol. Opt. Phys.* B **34** 3979
[58] Tarbutt M R and Silver J D 2002 *J. Phys. B: At. Mol. Opt. Phys.* **35** 1467
[59] Hosaka K, Crosby D N, Gaarde-Widdowson K, Smith C J, Silver J D, Kinugawa T, Ohtani S and Myers E G 2004 *Phys. Rev.* A **69** 011802
[60] Nakamura N *et al* 1998 *Rev. Sci. Instrum.* **69** 694
[61] Nakamura N, Tobiyama H, Nohara H, Kato D, Watanabe H, Currell F and Ohtani S 2006 *Phys. Rev.* A **73** 020705
[62] Watanabe H, Takahashi S, Tona M, Yoshiyasu N, Nakamura N, Sakurai M, Yamada C and Ohtani S 2006 *Phys. Rev.* A **74** 042901
[63] Nakamura N, Kato D and Ohtani S 2000 *Phys. Rev.* A **61** 052510
[64] Kato D, Nakamura N, Ohtani S and Sasaki A 2001 *Phys. Scr.* T **92** 126
[65] Beiersdorfer P, Bitter M, von Goeler S, Cohen S, Hill K W, Timberlake J, Walling R S, Chen M H, Hagelstein P L and Scofield J H 1986 *Phys. Rev.* A **34** 1297
[66] Beiersdorfer P *et al* 1988 *Phys. Rev.* A **37** 4153
[67] Nakamura N, Kato D and Ohtani S 2003 *Nucl. Instrum. Methods Phys. Res.* B **205** 57
[68] Widmann K, Beiersdorfer P, Brown G V, Crespo López-Urrutia J, Reed K J, Scofield J H and Utter S B 2000 *X-ray and Innershell Processes* ed R W Dunford *et al AIP Conf. Proc.* No. 506 (New York: AIP) p 444–66
[69] Nakamura N, Nakahara T and Ohtani S 2003 *J. Phys. Soc. Japan* **72** 1650
[70] Henderson J R *et al* 1990 *Phys. Rev. Lett.* **65** 705
[71] Beiersdorfer P *et al* 1996 *Phys. Rev.* A **53** 3974
[72] Beiersdorfer P, Brown G, Utter S, Neill P, Reed K J, Smith A J and Thoe R S 1999 *Phys. Rev.* A **60** 4156
[73] Takács E *et al* 1996 *Phys. Rev.* A **54** 1342
[74] Beiersdorfer P 1998 *Proc. the US–Japan Workshop and International seminar on Plasma Polarization Spectroscopy (Kyoto, Japan, 26–28 January 1998),* NIFS-PROC-37, ed T Fujimoto and P Beiersdorfer (Toki, Gifu: National Institute for Fusion Science) pp 67–89
[75] Nakamura N, Kato D, Miura N, Nakahara T and Ohtani S 2001 *Phys. Rev.* A **63** 024501
[76] Robbins D L, Faenov A Y, Pikuz T A, Chen H, Beiersdorfer P, May M J, Dunn J, Reed K J and Smith A J 2004 *Phys. Rev.* A **70** 022715
[77] Biedermann C, Förster A, Fußmann G and Radtke R 1997 *Phys. Scr.* T **73** 360
[78] Radtke R, Biedermann C, Fuchs T, Fußmann G and Beiersdorfer P 2000 *Phys. Rev.* E **61** 1966
[79] Radtke R, Biedermann C, Mandelbaum P and Schwob J L 2007 *J. Phys. Conf. Ser.* **58** 113
[80] Peacock N J, Mullane M G O, Barnsley R and Tarbutt M R 2008 *Can. J. Phys.* **86** 277
[81] Skinner C H 2008 *Can. J. Phys.* **86** 285
[82] Biedermann C, Radtke R, Fußmann G, Mandelbaum P and Schwob J L 2005 *Nucl. Instrum. Methods Phys. Res.* B **235** 126
[83] Gillaspy J D 1997 *Phys. Scr.* T **71** 99
[84] Morgan C A, Serpa F G, Takács E, Meyer E S, Gillaspy J D, Sugar J, Roberts J R, Brown C M and Feldman U 1995 *Phys. Rev. Lett.* **74** 1716
[85] Porto J V, Kink I and Gillaspy J D 2000 *Phys. Rev.* A **61** 054501
[86] Watanabe H, Crosby D, Currell F, Fukami T, Kato D, Ohtani S, Silver J and Yamada C 2001 *Phys. Rev.* A **63** 042513
[87] Utter S B, Beiersdorfer P and Träbert E 2003 *Phys. Rev.* A **67** 012508
[88] Kato D, Fukami T, Kinugawa T, Ohtani S, Watanabe H and Yamada C 2000 *Proc. the Int. Seminar on Atomic Processes in Plasmas (Toki, Japan, July 29–30 1999)* NIFS-PROC-44, ed I Murakami and T Kato (Toki: National Institute of Fusion Science)
[89] Beiersdorfer P *et al* 2001 *Phys. Rev.* A **64** 032506
[90] Beiersdorfer P, Crespo López-Urrutia J R, Utter S B, Träbert E, Gustavsson M, Forssén C and Mårtensson-Pendrill A-M 2003 *Nucl. Instrum. Methods* B **205** 62
[91] Takács E, Blagojevic B, Makónyi K, Le Bigot E-O, Szabó C I, Kim Y-K and Gillaspy J D 2006 *Phys. Rev.* A **73** 052505
[92] Crespo López-Urrutia J R, Beiersdorfer P, Widmann K and Decaux V 2002 *Can. J. Phys.* **80** 1687
[93] Biedermann C and Radtke R 2007 *Phys. Rev.* A **75** 066501
[94] Beiersdorfer P *et al* 2000 *Rev. Mex. Astron. Astrofís.* **9** 123
[95] Brown G V, Beiersdorfer P, Liedahl D A, Widmann K, Kahn S M and Clothiaux E J 2002 *Astrophys. J. Suppl.* **140** 589
[96] Kink I *et al* 2001 *Phys. Scr.* T **92** 454
[97] Laming J M *et al* 2000 *Astrophys. J.* **545** L161
[98] Beiersdorfer P *et al* 2002 *Astrophys. J. Lett.* **576** L169
[99] Beiersdorfer P, Bitter M, von Goeler S and Hill K W 2004 *Astrophys. J.* **610** 616

[100] Chen G X, Kirby K, Silver E, Brickhouse N S, Gillaspy J D, Tan J N, Pomeroy J M and Laming J M 2006 *Phys. Rev. Lett.* **97** 143201
[101] Brown G V, Beiersdorfer P and Widmann K 2001 *Phys. Rev.* A **63** 032719
[102] Gu M-F, Beiersdorfer P, Brown G V, Chen H, Boyce K R, Kelley R L, Kilbourne C A, Porter F S and Kahn S M 2004 *Astrophys. J. Lett.* **607** L143
[103] Chen G X, Kirby K, Silver E, Brickhouse N S, Gillaspy J D, Tan J N, Pomeroy J M and Laming J M 2007 *Phys. Rev. Lett.* **99** 109902
[104] Epp S W *et al* 2007 *Phys. Rev. Lett.* **98** 183001
[105] Draganić I, Crespo López-Urrutia J R, DuBois R, Fritzsche S, Shabaev V M, Soria Orts R, Tupitsyn I I, Zou Y and Ullrich J 2003 *Phys. Rev. Lett.* **91** 183001
[106] Beiersdorfer P, Decaux V, Elliott S, Widmann K and Wong K 1995 *Rev. Sci. Instrum.* **66** 303
[107] Beiersdorfer P, Osterheld A L, Decaux V and Widmann K 1996 *Phys. Rev. Lett.* **77** 5353
[108] Soria Orts R *et al* 2006 *Phys. Rev. Lett.* **97** 103002
[109] Lapierre A *et al* 2005 *Phys. Rev. Lett.* **95** 183001
[110] Träbert E, Beiersdorfer P, Utter S B, Brown G V, Chen H, Harris C L, Neill P A, Savin D W and Smith A J 2000 *Astrophys. J.* **541** 506
[111] Moehs D P and Church D A 1998 *Phys. Rev.* A **58** 1111
[112] Serpa F G, Gillaspy J D and Träbert E 1998 *J. Phys. B: At. Mol. Opt. Phys.* **31** 3345
[113] Brenner G, Crespo López-Urrutia J R, Harman Z, Mokler P H and Ullrich J 2007 *Phys. Rev. Lett.* **75** 032504
[114] Beiersdorfer P, Träbert E and Pinnington E H 2003 *Astrophys. J.* **587** 836
[115] Smith S J, Chutjian A and Lozano J A 2005 *Phys. Rev.* A **72** 062504
[116] Moehs D P and Church D A 1999 *Astrophys. J. Lett.* **516** L111
[117] Träbert E, Gwinner G, Wolf A, Knystautas E J, Garnir H-P and Todoir X 2002 *J. Phys. B: At. Mol. Opt. Phys.* **35** 671
[118] Bitter M, Hill K W, von Goeler S, Stodiek W, Beiersdorfer P, Rice J E and Ince-Cushman A 2008 *Can. J. Phys.* **86** 291
[119] Schneider M B *et al* 2008 *Can. J. Phys.* **86** 259
[120] May M J *et al* 2008 *Can. J. Phys.* **86** 251
[121] Safronova A S *et al* 2008 *Can. J. Phys.* **86** 267
[122] Beiersdorfer P 2003 *Annu. Rev. Astron. Astrophys.* **41** 343
[123] Lepson J, Beiersdorfer P, Bitter M and Kahn S M 2008 *Can. J. Phys.* **86** 175
[124] Wargelin B J, Beiersdorfer P and Brown G V 2008 *Can. J. Phys.* **86** 151
[125] Chen H and Beiersdorfer P 2008 *Can. J. Phys.* **86** 55
[126] Sapirstein J and Cheng K 2008 *Can. J. Phys.* **86** 25
[127] Träbert E 2008 *Can. J. Phys.* **86** 73
[128] Wargelin B J, Beiersdorfer P and Kahn S M 1993 *Phys. Rev. Lett.* **71** 2196
[129] Crespo López-Urrutia J R, Beiersdorfer P and Widmann K 2006 *Phys. Rev.* A **74** 012507
[130] Beiersdorfer P, Osterheld A L, Scofield J, Wargelin B and Marrs R E 1991 *Phys. Rev. Lett.* **67** 2272
[131] Ralchenko Y, Tan J N, Gillaspy J D, Pomeroy J M and Silver E 2006 *Phys. Rev.* A **74** 042514
[132] Träbert E, Beiersdorfer P, Brown G V, Boyce K, Kelley R L, Kilbourne C A, Porter F S and Szymkowiak A 2006 *Phys. Rev.* A **73** 022508
[133] Yao K, Andersson M, Brage T, Hutton R, Jönsson P and Zou Y 2007 *Phys. Rev. Lett.* **98** 269903
[134] Träbert E, Beiersdorfer P and Brown G V 2007 *Phys. Rev. Lett.* **98** 263001
[135] Bergström I, Carlberg C, Fritioff T, Douysset G, Schönfelder J and Schuch R 2002 *Nucl. Instrum. Methods Phys. Res.* A **487** 618
[136] Stöhlker T *et al* 2003 *Nucl. Instrum. Methods Phys. Res.* B **205** 156
[137] Currell F J *et al* 2005 *Phys. Scr.* T **120** 53
[138] Kentsch U, Werner T, Zschornack G, Grossmann F, Ovsyannikov V P and Ullmann F 2001 *Eur. Phys. J.* D **17** 297
[139] Watanabe H *et al* 2005 *Nucl. Instrum. Methods Phys. Res.* B **235** 261
[140] May M J, Finkenthal M, Soukhanovskii V, Stutman D, Moos H W, Pacella D, Mazzitelli G, Fournier K, Goldstein W and Gregory B 1999 *Rev. Sci. Instrum.* **70** 375